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INVESTIGATION OF A TEMPERATURE-STABILIZED, PHOTON-COUPLED, ISOLATOR-PREAMPLIFIER CIRCUIT

Jack Lenton Welch

ARO, Inc.

September 1968

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FOREWORD

The work reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), in support of a project performed for Air Force Aero-Propulsion Laboratory (AFAPL), under Program Element 62405214, Project 5350, Task 535004.

The results described herein were obtained under the provisions of Contract F40600-69-C-0001 by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), operating contractor of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was performed from January 1967 to March 1968 as test instrumentation and/or equipment development support of ARO Project No. RW0637, and the manuscript was submitted for publication on July 26, 1968.

This report was prepared as a thesis as partial fulfillment of the requirements for the degree of Master of Science at the University of Tennessee Space Institute and submitted in March 1968.

The writer wishes to thank his major professor, Dr. F. M. Shofner, for permission to use his original work and for his counseling during the preparation of the material for this thesis.

This technical report has been reviewed and is approved.

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ABSTRACT

A theoretical and experimental analysis of a temperature-stabilized, photon-coupled, isolator-preamplifier circuit was conducted. Input signals were applied to a gallium arsenide diode which in turn emitted infrared radiation in proportion to the instantaneous forward current. The radiation was guided through a light pipe into a silicon PIN photodiode. The signals which resulted at the photodiode were therefore controlled by, but electrically isolated from, the input. Both the input circuit and the preamplifier were investigated for temperature effects, and circuits were designed to limit these effects.

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NOMENCLATURE

A	Junction area
A_o	Circuit voltage gain
A_{vt}	Voltage gain
$\mathring{A}$	Angstrom units
a	Amperes
ac	Alternating current
b'	Internal-base terminal
°C	Centigrade degrees
C	Capacitance
$C_{b'c}$	Collector-to-internal-base capacitance
$C_{b'e}$	Capacitance from b' to emitter
C_{scope}	Capacitance of oscilloscope
c	Speed of light
dc	Direct current
D_e	Charge-carrier diffusion constant (dynamical property of minority carrier electrons)
D_h	Charge-carrier diffusion constant (dynamical property of minority carrier holes)
E	Energy of photons
Ego	Width of energy gap
f_τ	Bandwidth in hertz
G	Transfer gain

GaAs	Gallium arsenide diode
gm	Transconductance
h	Planck's constant
hie	Small signal hybrid parameter
I	Total diode current
I_F	Diode forward current
I_o	Diode operating current
I_s	Diode reverse saturation current
i	Instantaneous current
k	Boltzmann's constant
L_e	Carrier diffusion length for electrons
L_h	Carrier diffusion length for holes
ℓn	Natural logarithm
N_A	Acceptor concentration on the P-type side of an abrupt P-N junction
N_D	Donor concentration on the P-type side of an abrupt P-N junction
n_N	Concentration of electrons in the N-region
n_i	Intrinsic carrier concentration
n_P	Concentration of electrons in the P-region
pf	Picofarads
p_N	Concentration of holes in the N-region
p_P	Concentration of holes in the P-region
q	Charge of an electron

r_{ac}	Dynamic resistance
r_b	Small signal base resistance
R_{dc}	Static resistance
T	Absolute temperature in Kelvin degrees
V	Volts
V_B	Value of the potential barrier in electron-volts
V_F	Forward bias voltage
$V_{b'e}$	Voltage b' to emitter
v	Instantaneous voltage
β	Small-signal CE short-circuit current gain
Δ	Small change
ϵ	Base of the natural logarithm
λ	Wavelength of light in angstrom units
ν	Frequency
ω_β	Bandwidth in radians

CHAPTER I
INTRODUCTION

I. STATEMENT OF THE PROBLEM

The ability to amplify small current or voltage changes about a high base level, while isolating the amplifier output circuit from the input circuit, is a very important problem of instrumentation. The problem has given rise to this investigation to produce an isolator-amplifier which is capable of a frequency response (±3 decibels) over a range from zero hertz to 1.5 megahertz, direct-current isolation between input and output of 10,000 volts, output variation less than 0.5 millivolts for temperatures between ambient and 60°C, and with an overall voltage transfer of the order of unity.

II. JUSTIFICATION OF THE PROBLEM

A need has arisen in the field of magnetohydrodynamics (MHD) to measure the changing value of the current at various electrodes along the conducting side wall of a Hall-type generator (1)[1]. These measured values must be recorded on

[1]Numbers in parentheses refer to similarly numbered references in the bibliography.

magnetic tape to facilitate data reduction. The points of measurement along the Hall generator vary in steady-state potential above ground from zero to 5,000 volts. This high potential must be isolated from the magnetic tape input while allowing changes from the steady-state level to be recorded. The changes in steady-state level have frequency components of interest from zero hertz to 100 kilohertz.

The process of designing direct-coupled (d-c) amplifiers which cover the desired frequency range is well covered in the literature (2, 3, 4, 5). However, an amplifier previously assembled or designed which would meet all the application requirements was not available.

A photon-coupled isolator-preamplifier was designed by Dr. F. M. Shofner, University of Tennessee Space Institute, for acquisition of MHD generator current fluctuations. This design was developed by Mrs. P. Chang, also of The University of Tennessee Space Institute, and J. L. Welch, of ARO, Incorporated. The original design concept incorporated a photon-coupled isolator unit which constituted the input to a three-stage transistor amplifier. The amplifier exceeded the required criteria for voltage isolation (10,000 volts). However, the frequency response was very limited on the low end. A flat frequency response of ± 3 decibels over a range from 100 hertz to 100 kilohertz was achieved. The amplifier was capable of discerning changes in the input signal as low

as five millivolts. The particular shortcoming of the original amplifier was failure of response below 100 hertz.

In addition to the amplifier designed by Shofner, several switching circuits are presented by Hewlett Packard Associates (6) which make use of the gallium arsenide photon-coupled isolator unit. While none of these circuits satisfy the above mentioned requirements, they do offer much design information.

III. PROPOSED SOLUTION

Figure 1 shows the isolator-preamplifier configuration, proposed and developed as a solution to the isolation problem. The circuit consists of a wide band photon-coupled isolator and a direct-coupled preamplifier. The unit has been designed to accept small signals developed across the low input shunt resistor (R_s). The electrical inputs are applied to the gallium arsenide diode which in turn emits infrared radiation in proportion to the instantaneous forward current. The radiation is guided through a light pipe into a silicon PIN photodiode. The signals resulting at the photodiode are, therefore, controlled by, but electrically isolated from, the input. The gallium arsenide diode is biased by a pair of 1N661 diodes for temperature compensation. The output of the photodiode is direct coupled into the preamplifier unit, resulting in the transfer of

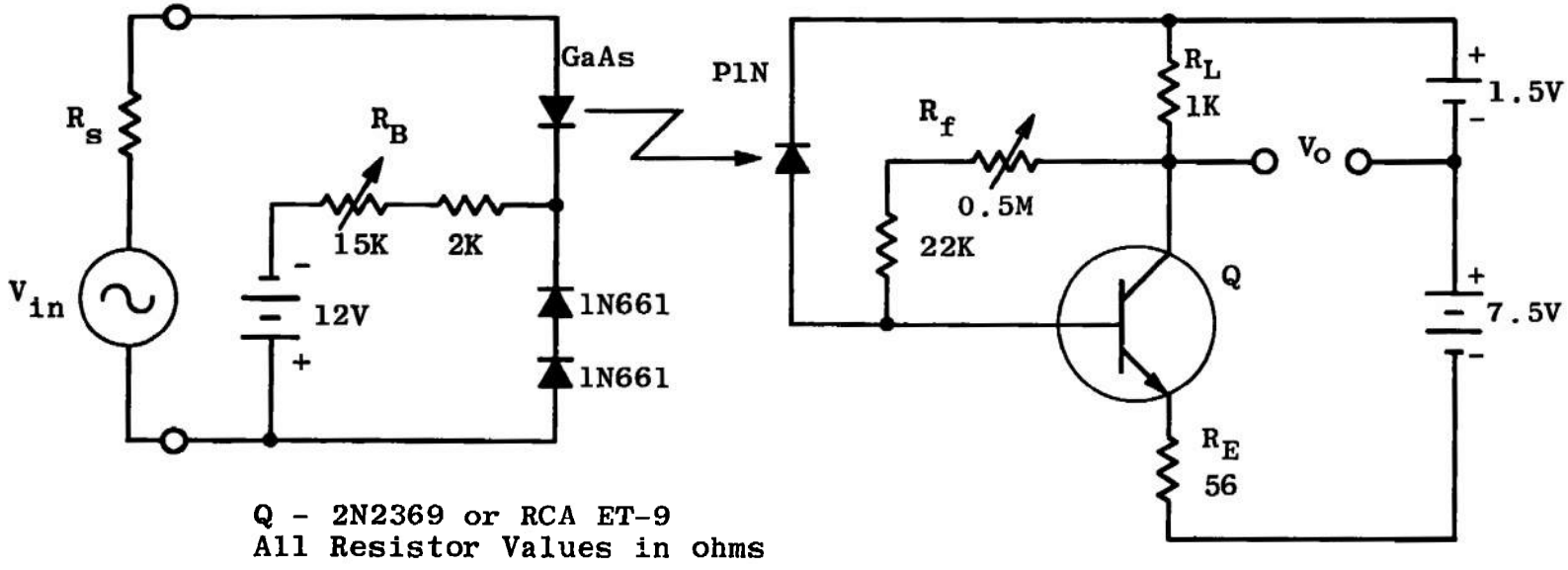


Figure 1. Photon-coupled isolator-preamplifier circuit.

electrical signals of zero frequency. The upper frequency range of the unit is determined by the preamplifier, since the isolator unit has the capability to pass frequencies to ten megahertz.

IV. SCOPE OF THE INVESTIGATION

The major point of concern in this investigation was to determine if the photon-coupled isolator could provide effective isolation and serve as the input stage of a direct-coupled preamplifier. In general, direct-coupled amplifiers are extremely hard to stabilize against temperature changes. In this investigation, three primary sources of temperature drift were considered: the gallium arsenide diode forward voltage; the photon emission, coupling, and photodiode detection efficiencies; and the preamplifier transistor current gain and reverse saturation current. No attempt was made to temperature-stabilize the batteries although this is a recognized and important problem area.

Chapter II constitutes a study of the characteristics of diodes with special concentration on the effects of temperature variation. Also included in this chapter is a short explanation of the operation of the photon-coupled isolator. The study of Chapter II led to a biasing arrangement for the gallium arsenide diode which allowed for low

input impedance, direct coupling, and temperature stabilization of the input circuit.

Chapter III presents a discussion of the isolator-preamplifier circuit. The overall gain of the circuit and the high break frequency are calculated.

Chapter IV provides an experimental investigation of the photon-coupled isolator-preamplifier. This chapter verifies experimentally those factors predicted in the theoretical study. The effects of voltage and temperature changes on the current through the GaAs diode are investigated. Next the effects of voltage and temperature changes on the current through the 1N661 diode are considered. The GaAs diode is then biased by a circuit composed of 1N661 diodes, and the effects of temperature on the circuit are investigated.

The effects of temperature on the forward gain (signal transfer from GaAs diode to photodiode) are next considered.

The coupling of the photodiode to the input of the preamplifier constituted the last major obstacle in producing a direct-coupled amplifier. This coupling and the temperature stability of the overall circuit are investigated. The experimentally determined gain and the frequency response are also presented.

Chapter V gives the conclusions reached by this investigation and a discussion of the problem which still exists.

CHAPTER II
THE CHARACTERISTICS OF SEMICONDUCTOR DIODES

I. THE DIODE EQUATION

The total external current which flows through a diode is given by Pierce (3) as

$$I = I_s \left(\varepsilon^{qV/kT} - 1 \right) , \qquad [1]$$

where

I_s is the reverse saturation current,

V is the external bias applied, and

I is the total diode current.

For positive values of voltage (forward bias), it can be seen that the forward current increases exponentially. A sufficiently high forward current will result in destruction of the diode by overheating. Also it can be seen that an increase in negative voltage (reverse bias) carries with it no appreciable increase in negative current. This is true only to a certain degree. An excessive negative bias will cause diode breakdown, and excessive negative current will flow and again result in the destruction of the diode.

Two very important diode properties can be obtained from an examination of the diode characteristic curve in

Figure 2. These properties are the dynamic and static resistance. The static or d-c resistance is found by determining the inverse slope of a line drawn from the origin to the point on the curve which represents the current through the diode. The dynamic or a-c resistance of the diode is determined by finding the inverse slope of the line tangent to the voltage-current curve at the point of operation. The dynamic curve then represents the ratio of a change in voltage to a change in current. Figure 2 shows clearly that neither the alternating current nor the direct current resistance of the diode is constant, but that both depend upon the current flowing in the diode.

The dynamic resistance of the diode can also be found by taking the derivative of the diode equation with respect to the voltage. Thus by referring to Equation 1,

$$\frac{dI}{dV} = \frac{qI_s}{kT} \varepsilon^{qV/kT} \quad . \qquad [2]$$

But from Figure 2,

$$I_s \varepsilon^{qV/kT} = I_o + I_s \quad , \qquad [3]$$

where I_o is the current at the operating point. Since I_o is normally much greater than I_s, then

$$I_s \varepsilon^{qV/kT} \approx I_o \approx I \qquad [4]$$

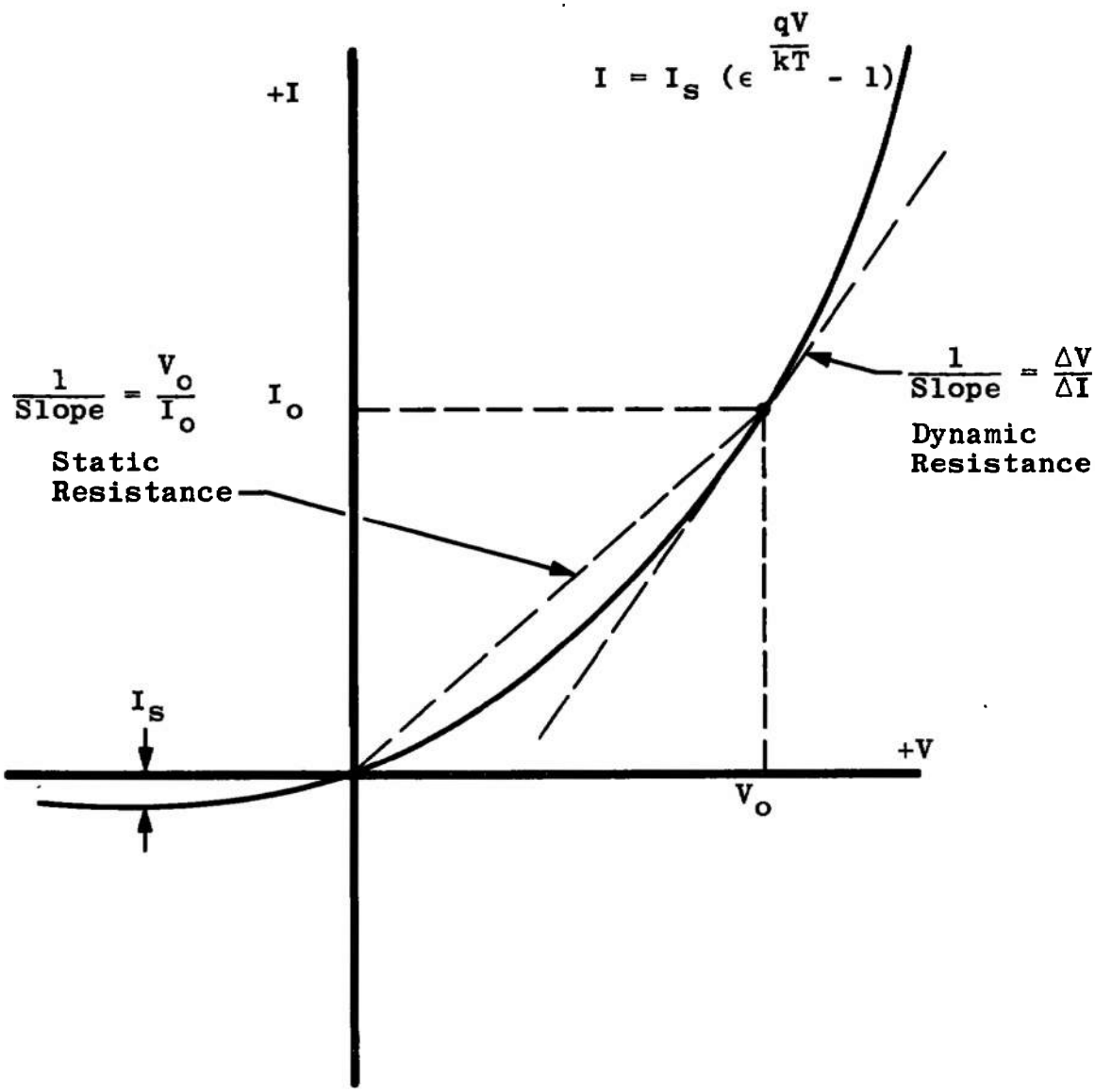


Figure 2. Graphical method for determining static and dynamic resistance of a diode.

and

$$\frac{dI}{dV} \approx \frac{qI}{kT} \quad . \qquad [5]$$

The dynamic resistance (r_{ac}) was found above to be

$$r_{ac} = \frac{dV}{dI} \quad . \qquad [6]$$

Therefore, since

$$\frac{dI}{dV} = \left(\frac{dV}{dI}\right)^{-1} \quad , \qquad [7]$$

substitution of Equation 6 into Equation 7 gives

$$r_{ac} \approx \frac{kT}{qI} \quad . \qquad [8]$$

For room temperature, T is 300°Kelvin and

$$r_{ac} \approx \frac{0.026}{I} \text{ ohms} \quad . \qquad [9]$$

Since both the a-c and the d-c resistance of the diode depend on the shape of the diode characteristic curve and since the shape of the characteristic curve depends on the temperature, it can easily be seen that the overall operation and stability of the diode are temperature dependent.

Although it has been seen that the diode equation contains the absolute temperature explicitly in the exponent

(qV/kT), the primary temperature dependent characteristic of the diode results from the implicit temperature dependence of the saturation current I_s (3).

II. TEMPERATURE DEPENDENCE

Temperature dependence of I_s. The temperature dependence of I_s is mainly a consequence of the strong dependence of the equilibrium minority-carrier concentrations on temperature. These equilibrium concentrations are related to the intrinsic carrier concentrations and to the doping by the equations,

$$p_N \approx \frac{n_i^2}{N_D} \qquad [10]$$

and

$$n_P \approx \frac{n_i^2}{N_A} , \qquad [11]$$

where

n_i is the intrinsic carrier concentration,

N_D is the donor concentration on the N-type side of an abrupt junction,

p_N is the hole concentration in the N-region,

n_P is the electron concentration in the P-region, and

N_A is the acceptor concentration on the P-type side of an abrupt P-N junction.

The saturation current (I_s) is approximated (7) by

$$I_s \approx Aqn_i^2 \left(\frac{D_h}{N_D L_h} + \frac{D_e}{N_A L_e} \right) , \qquad [12]$$

where

A is the junction area,

q is the magnitude of the electronic charge,

D_h is the charge-carrier diffusion constant (dynamical property of minority carrier holes),

D_e is the charge-carrier diffusion constant (dynamical property of minority carrier electrons),

L_h is the carrier diffusion length for holes, and

L_e is the carrier diffusion length for electrons.

In Equation 12, the semiconductor parameters inside the parentheses are fairly constant with temperature (7). An examination of the intrinsic carrier concentration (n_i) shows a strong temperature dependence (7) since

$$n_i^2 = BT^3 \varepsilon^{-Ego/kT} , \qquad [13]$$

where

B is a constant,

k is Boltzmann's constant, and

Ego is the width of the energy gap .

Taking the logarithm of Equation 13 yields

$$\ell n\ (n_i^2) = \ell n\ (BT^3) - \left(\frac{Ego}{k}\right)\left(\frac{1}{T}\right) . \qquad [14]$$

Within the operating temperature of most diodes, the temperature dependence of n_i^2 is controlled by the (Ego/k) $\frac{1}{T}$ factor (7). A plot of $\ell n\ (n_i^2)$ versus $\frac{1}{T}$ is then approximately linear with a slope of -Ego/k.

The fractional change in n_i^2 per unit change in temperature very closely approximates the fractional change in I_s per unit change in temperature. It is found experimentally that for most diodes I_s approximately doubles every ten centigrade degrees in germanium and every six centigrade degrees in silicon (7).

Temperature dependence of current for constant voltage. The temperature coefficient of the diode current for fixed forward bias can be determined by evaluating $(\partial I/\partial T)_V$ from the diode equation.

If $\epsilon^{qV/kT}$ is very much greater than one,

$$\left.\frac{\partial I}{\partial T}\right|_V = \frac{\partial}{\partial T}\left(I_s \epsilon^{qV/kT}\right) \qquad [15]$$

or

$$\left.\frac{\partial I}{\partial T}\right|_V = - I_s \frac{qV}{kT^2} \varepsilon^{qV/kT} + \frac{\partial I_s}{\partial T} \varepsilon^{qV/kT} , \qquad [16]$$

but since $\varepsilon^{qV/kT} >> 1$,

$$\frac{I}{I_s} \approx \varepsilon^{qV/kT} ; \qquad [17]$$

then

$$\left.\frac{\partial I}{\partial T}\right|_V \approx I \left(\frac{1}{I_s} \frac{\partial I_s}{\partial T} - \frac{qV}{kT^2}\right) . \qquad [18]$$

But from Gray (7),

$$Ego = kT^2 \frac{1}{I_s} \frac{\partial I_s}{\partial T} . \qquad [19]$$

Therefore,

$$\frac{1}{I} \left.\frac{\partial I}{\partial T}\right|_V \approx \frac{Ego-qV}{kT^2} . \qquad [20]$$

Over the operating range of the transistor, the term on the right side of Equation 20 is approximately constant. Then

$$\frac{1}{I} \frac{dI}{dT} \approx C_1 , \qquad [21]$$

for constant V. Then

$$\frac{dI}{I} \approx C_1 dT \ , \qquad [22]$$

$$\ell nI \approx C_1 T \ , \qquad [23]$$

and

$$I \approx \epsilon^{C_1 T} \ . \qquad [24]$$

From Equation 24, it can be seen that the current in an idealized junction diode increases nearly exponentially with temperature for fixed voltage.

Temperature dependence of voltage for constant current. The temperature coefficient of the diode voltage for fixed forward current is found by evaluating $(\partial V/\partial T)_I$ from the diode equation. From Equation 1,

$$\frac{I+I_s}{I_s} = \epsilon^{qV/kT} \ . \qquad [25]$$

However, if $I >> I_s$, then

$$\frac{I}{I_s} = \epsilon^{qV/kT} \ , \qquad [26]$$

$$\ell n \left(\frac{I}{I_s}\right) = \frac{qV}{kT} \ , \qquad [27]$$

$$qV = kT\ell n\left(\frac{I}{I_s}\right), \text{ where I is constant,} \qquad [28]$$

and

$$q \cdot \frac{\partial V}{\partial T} = k\ell n \frac{I}{I_s} + kT \frac{\partial}{\partial T} \left(\ell n \frac{I}{I_s} \right) \quad [29]$$

and

$$q \cdot \frac{\partial V}{\partial T} = k \left(\ell n \frac{I}{I_s} \right) + kT \frac{I_s}{I} \left(\frac{-I}{I_s^2} \right) \frac{\partial I_s}{\partial T} . \quad [30]$$

Substituting Equation 28 into Equation 30 gives

$$q \cdot \frac{\partial V}{\partial T} = \frac{qV}{T} - \frac{kT}{I_s} \frac{\partial I_s}{\partial T} \quad [31]$$

or

$$\frac{\partial V}{\partial T} = \frac{V}{T} - \frac{kT}{q} \frac{1}{I_s} \frac{\partial I_s}{\partial T} . \quad [32]$$

Substituting Equation 19 into Equation 32 yields

$$\left. \frac{\partial V}{\partial T} \right|_I \approx - \frac{Ego/q - V}{T} . \quad [33]$$

By allowing the same assumption as for Equation 21,

$$\frac{dV}{dT} \approx - C_2 , \quad [34]$$

where C_2 is a constant. Then

$$dV \approx - C_2 dT \quad [35]$$

and

$$V \approx - C_2 T \ . \qquad [36]$$

From Equation 36, it can be seen that the voltage in an idealized junction diode decreases nearly linearly with temperature for fixed current.

III. REQUIREMENT FOR CONSTANT CURRENT WITH VARYING TEMPERATURE

The variations in the static and dynamic resistance and in forward current for an incremental change in forward voltage can be obtained from Figure 2, page 9. The values thus obtained are for a constant temperature.

Figure 3 shows a diode circuit with forward bias. The resistor (R_B) represents the equivalent bias source resistance of the circuit. For this circuit if V_F changes with temperature, I_F must also change. If, however, the battery (V) is replaced by a voltage source which is also a function of temperature, it is possible for the current I_F to be independent of temperature. By assuming that both V and V_F are functions of temperature and current, Ohm's law for the circuit in Figure 3 yields

$$I_F = \frac{V(T,I_F) - V_F(T,I_F)}{R_B} \ . \qquad [37]$$

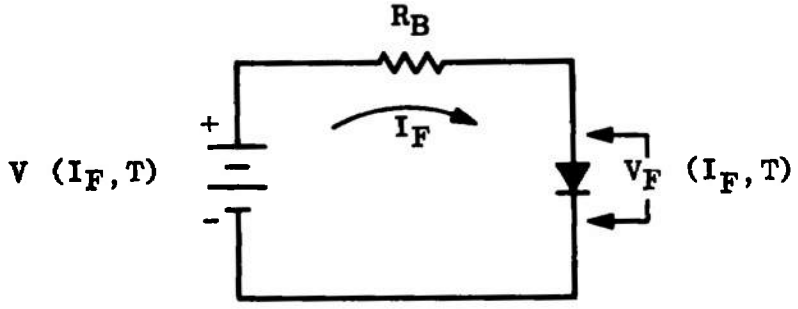


Figure 3. Forward biased diode circuit.

For the current (I_F) to be independent of temperature changes

$$\frac{\partial I_F}{\partial T} = 0 \ , \qquad [38]$$

and this implies that

$$\frac{\partial V}{\partial T} = \frac{\partial V_F}{\partial T} \ . \qquad [39]$$

Equation 39 leads to the conclusion that for the forward current through a diode to remain constant for an increase in temperature, the change in bias voltage (V) must be equal to the change in V_F.

The analysis thus far points out that if a biasing device whose temperature dependence matches that of the GaAs diode can be found, the GaAs diode current can be held constant for varying temperatures. This same reasoning can be carried into the preamplifier unit.

IV. THE PHOTON-COUPLED ISOLATOR

The wideband photon-coupled isolator which is used at the input of the direct-coupled amplifier is composed of a gallium arsenide (GaAs) diode light emitter and a PIN silicon photodiode.

In general, light emitters are primarily gallium arsenide P-N junction diodes. When the junction is forward

biased, a narrow, primarily noncoherent, 8970-angstrom unit wavelength light band is emitted. Figure 4 shows the basic diagram of the gallium arsenide diode.

Electrons which diffuse across the junction from the N-doped side recombine with holes and give up optical energy. Similarly, optical energy is given up when holes diffuse across the junction from the P-doped side and recombine with electrons. The energy of the photons thus radiated corresponds closely to the energy band gap of the semiconductor material used in the junction. Pure GaAs has a 1.513 electron-volt band gap (8). The frequency corresponding to this energy band gap is given by the equation

$$\nu = E/h \ , \qquad [40]$$

where

ν is the frequency in hertz,

E is the energy of the photons in joules, and

h is Planck's constant = 6.6234×10^{-34} joule second.

Using this equation and the equation for the speed of light gives

$$\lambda = c/\nu = \frac{hc}{E} = \frac{1.24 \times 10^4}{E'} \ , \qquad [41]$$

where E' is the band gap energy in electron volts. The wavelength, λ, in angstroms, of the photons emitted from the

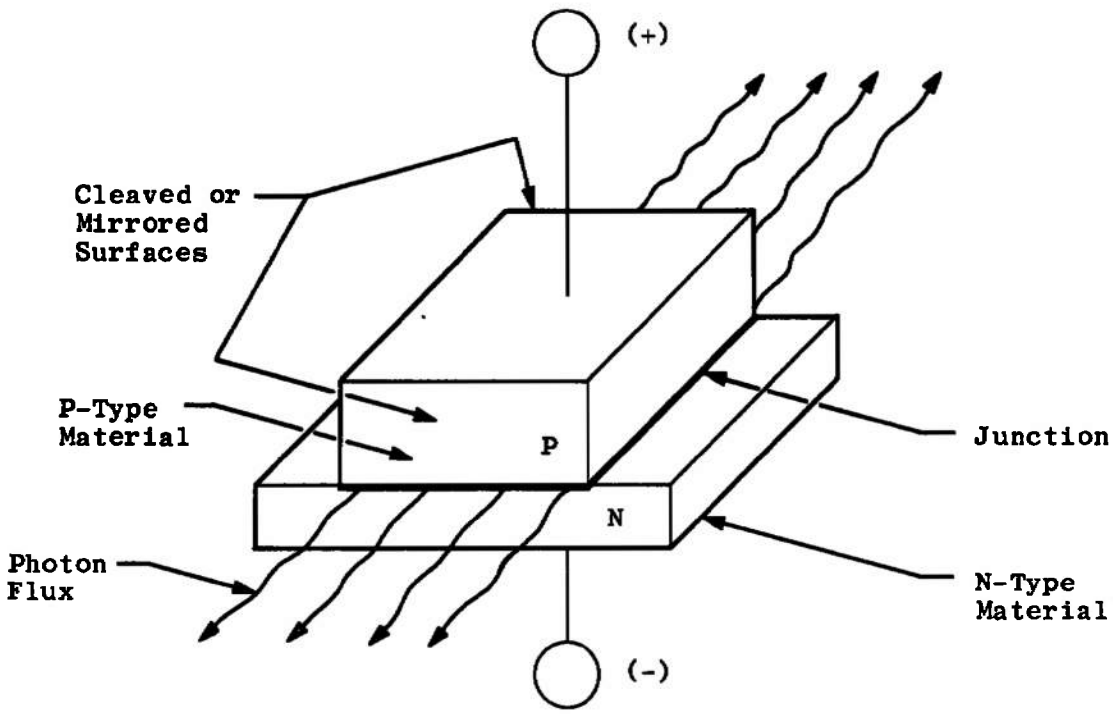


Figure 4. Basic gallium arsenide diode.

diode can be found by

$$\lambda = \frac{1.24 \times 10^4}{1.513} = 8190 \text{ Å} . \qquad [42]$$

A shift in the wavelength can be obtained by doping the GaAs. The Hewlett Packard Associates hpa 4303 radiates a distribution of photons with a peak wavelength of 9000 angstroms (9).

The energy output of a light-emitting diode ranges from 0.5×10^{14} to 2×10^{14} photons per second for 100 milliamperes in the diode. Light output increases linearly with current after a few milliamperes in the diode (10). Therefore, the light emitted from the gallium arsenide diode is proportional to the electrical input signals.

The radiated signal from the GaAs diode is guided through a light pipe into a light detector. There are basically two forms of solid-state light detectors: photoconductive and photovoltaic. In both, hole-electron pairs are produced in the semiconductor when entering photons have an energy greater than the band gap. The photoconductor carriers are either swept out by a bias potential or trapped, and a current persists until recombination takes place. Thus the length of time in which current persists (recombination time) is a factor in the gain (electrons/photon) of the device. In the P-N junction detector, a reverse bias field

creates a depletion region, and recombination occurs as soon as the carriers cross the gap. Thus, the device normally has less than unity current gain (11).

Although the P-N junction offers less gain than the ordinary photoconductive bar detector, it is much faster. In normal operation, P-N junctions have external quantum gains on the order of 0.3 with a frequency response to several megahertz and wavelength response to several micrometers (11).

A photovoltaic output from the photodiode is available even without bias although a reverse bias is recommended for enhancement of the response time and maintenance of high photon-to-electron conversion efficiency (6). Figure 5 is a schematic diagram of a properly biased isolator unit.

As seen from the above discussion, photon-coupled isolation consists of transferring electrical signals from one circuit to another by a stream of photons. While forward current in the gallium arsenide diode produces radiation which the silicon photodiode can detect, the reverse cannot happen. The electrical signal is, therefore, effectively transferred in only one direction. The Hewlett Packard hpa 4303 isolator is capable of withstanding a 20,000 volt difference between input and output. This characteristic, along with the capability of the device to operate on direct current as well as alternating current signals,

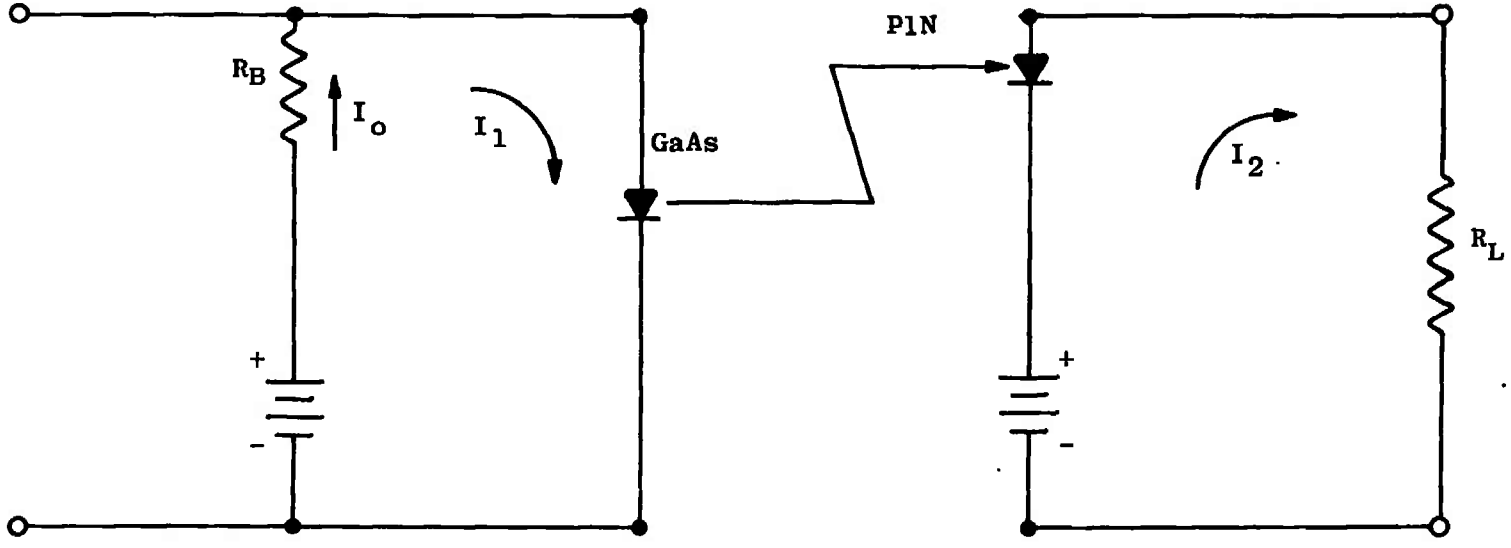


Figure 5. Schematic diagram of a properly biased photon-coupled isolator.

makes the isolator ideal for use in measuring current or voltage fluctuations inside a Hall-type magnetohydrodynamic generator or for any other application requiring high voltage isolation.

CHAPTER III
CIRCUIT ANALYSIS

I. CIRCUIT DESCRIPTION

The complete photon-coupled isolator-preamplifier circuit is shown in Figure 1, page 4. The circuit shows the GaAs diode biased by two 1N661 silicon diodes. A search of the literature (12, 13) showed that the 1N661 diode had temperature characteristics similar to those of the GaAs diode. The use of a diode biasing arrangement results in a very low dynamic impedance in series with the GaAs diode. Since no capacitors were required in this bias arrangement, direct coupling was achieved. The temperature characteristics of the 1N661 diode also compensate for the change in current through the GaAs diode for a change in temperature. This compensation is further discussed in Chapter IV.

The fifteen-ohm input resistor (R_s) probably appears rather large since, as will be seen later, it directly affects the gain of the overall amplifier. The resistor aids in the stability of the input circuit for changes in temperature. The resistor also allows for insertion of a signal using a high impedance laboratory oscillator for the experimental work.

The transfer of the input signal from the GaAs diode to the PIN photodiode is through photon coupling. The gain of the transfer is 3×10^{-4}. This loss in signal is offset by the fact that isolation of the output from the input up to 20,000 volts is accomplished.

The current generated in the PIN diode depends on the current flowing through the GaAs diode and is most insensitive to small changes in its reverse bias. For this reason, the PIN diode acts like a constant current source feeding the base of the common emitter transistor circuit.

The preamplifier circuit makes use of a silicon transistor (type 2N2369). Although this transistor is normally used as a computer switching unit, its high speed and temperature stability make it useful here. At ambient temperature, the RCA ET-9 transistor, a germanium type, will operate equally well in this circuit.

Normally, a major source of temperature instability in an amplifier using silicon transistors is the decrease in V_{BE} with temperature. However, for current source bias, as used here, this effect is minimized and the low I_{CO} (reverse saturation current) of silicon devices is used to advantage. A small change in voltage between the base and emitter of the transistor, therefore, does not control the base current. Also, the 2N2369 transistor is a silicon type and, therefore, the effects of temperature change on I_{CO} below 100°C

are small compared with the PIN current. As will be shown in Chapter IV, the change in the GaAs diode-to-PIN transfer characteristic is in a direction to oppose the effects of the reverse saturation current. In early experiments, a 1N661 diode was placed between the base and the emitter to decrease the effects of the reverse saturation current. No appreciable increase in circuit stability was realized by use of the diode.

A second major source of temperature instability which was expected was that of the forward current transfer ratio (β). Normally, β increases almost linearly with temperature. There are three factors in the design of the circuit which tend to maintain a constant collector current with temperature change. First, the decrease in the GaAs diode-to-PIN transfer characteristic, as mentioned previously, lowers base current with temperature. Second, the feedback network from collector to base decreases the base current for an increase in collector current. The third stabilizing factor in the circuit is the emitter resistor. This resistor has much the same effect on stability as does the collector-base feedback resistor. Although the collector-base feedback resistor and the emitter resistor tend to decrease the overall gain, they also make the circuit less dependent on the transistor characteristics(3). The

feedback resistor lowers the input impedance of the circuit while not appreciably altering the output impedance.

The output of the circuit is taken between the collector and a portion of the bias battery. By using this arrangement the feedback potentiometer can be adjusted to yield zero output of the amplifier for zero signal input to the GaAs diode.

II. CALCULATED CIRCUIT VOLTAGE GAIN

In the calculation of the circuit voltage gain the bias current is neglected and only the a-c components are considered. A simplified circuit diagram is shown in Figure 6. In the diagram G represents the GaAs-PIN diode transfer function, i_1 is the current flowing in the GaAs diode, and r_d is the PIN diode resistance. From this diagram

$$i_{R_f} = \frac{v_i - v_o}{R_f} . \qquad [43]$$

But since $R_L << R_f$,

$$v_o \approx - i_c R_L = - \beta i_b R_L . \qquad [44]$$

Then

$$i_{R_f} \approx \frac{v_i + \beta i_b R_L}{R_f} , \qquad [45]$$

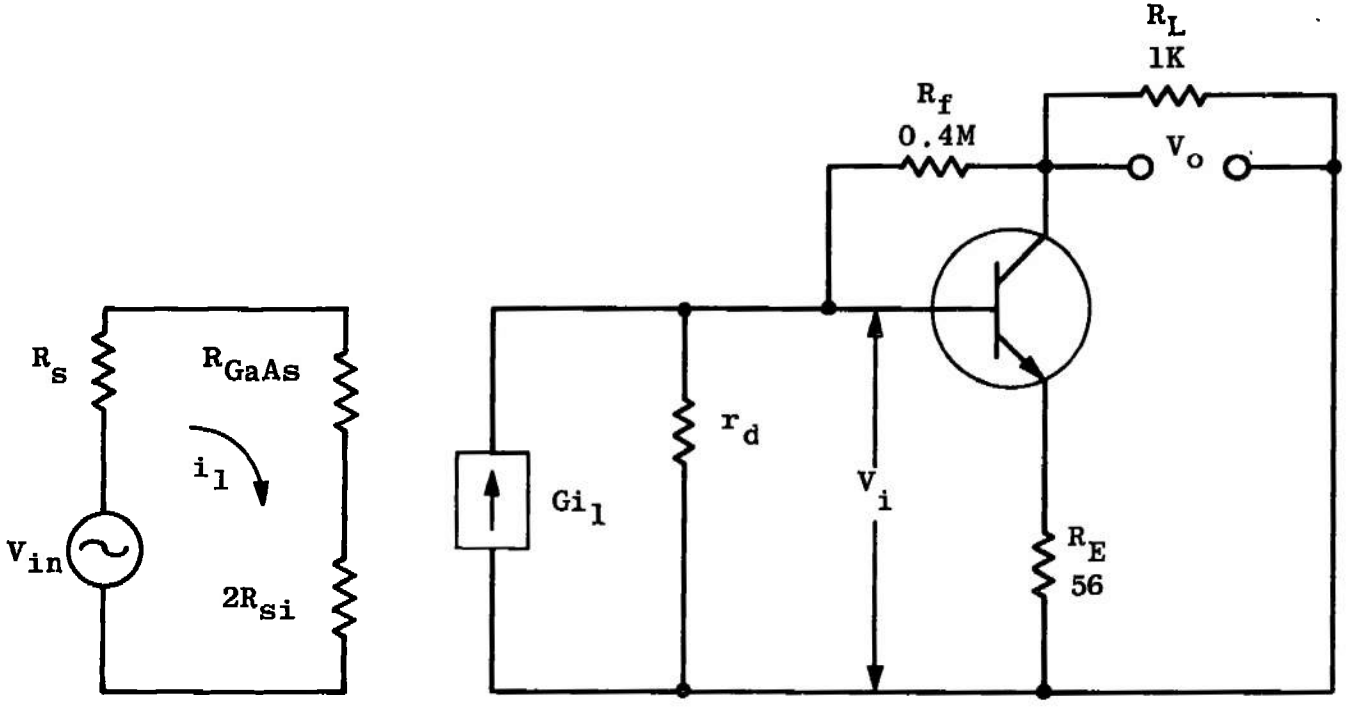


Figure 6. Simplified circuit diagram for the isolator-preamplifier.

but

$$i_b = \frac{v_i}{R_i} , \qquad [46]$$

and, therefore,

$$i_{R_f} \approx \frac{v_i + v_i \beta \frac{R_L}{R_i}}{R_f} = \frac{v_i \left(1 + \beta \frac{R_L}{R_i}\right)}{R_f} \qquad [47]$$

or

$$i_{R_f} \approx \frac{\frac{v_i}{R_f}}{1 + \beta \frac{R_L}{R_i}} . \qquad [48]$$

The common emitter input resistance is found by

$$R_i = hie + (\beta + 1)R_E = 2 \times 10^3 + (100 + 1)56 = 7.6 \text{ kilohms} . \qquad [49]$$

From Equations 48 and 49,

$$i_{R_f} \approx \frac{\frac{v_i}{400 \times 10^3}}{1 + 100\left(\frac{10^3}{7.6 \times 10^3}\right)} = \frac{v_i}{28.35 \times 10^3} . \qquad [50]$$

Then substituting Equation 49 into Equation 46 gives

$$i_b = \frac{v_i}{hie+(\beta+1)R_E} = \frac{v_i}{7600} \quad . \qquad [51]$$

Equations 46 and 48 suggest the equivalent circuit in Figure 7. From Figure 7, by neglecting r_d and using the current-splitting formula,

$$i_b = \frac{28.35x10^3}{28.35x10^3+7.6x10^3} Gi_1 = 0.8\ Gi_1 \quad . \qquad [52]$$

Substituting Equation 52 into Equation 44 yields

$$v_o = -\beta i_b R_L = -\ (10^2)(0.86\ Gi_1)(10^3) \qquad [53]$$

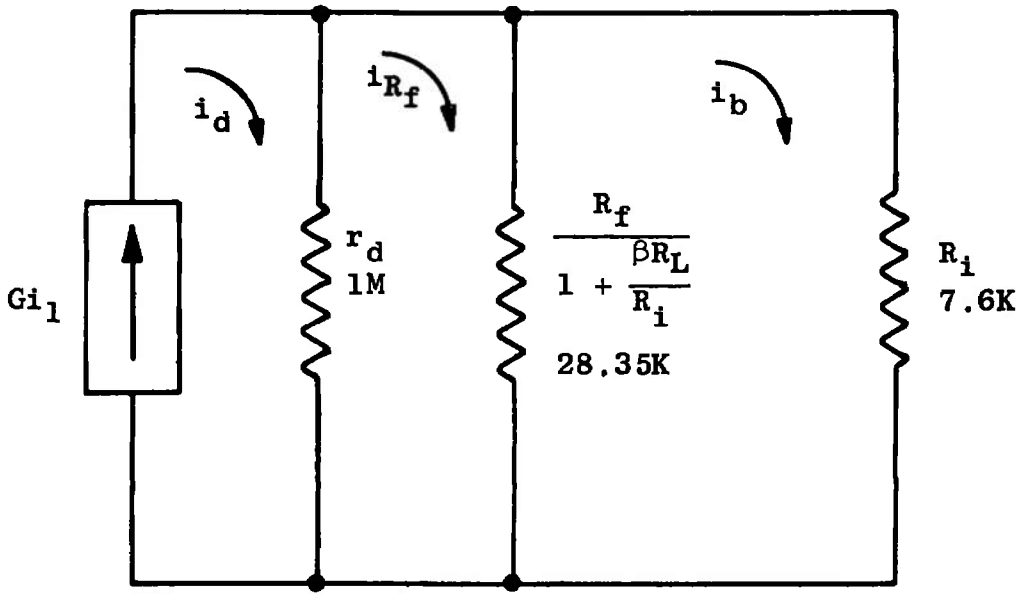
or

$$v_o = -0.8 \times 10^5\ Gi_1 \quad . \qquad [54]$$

The current (i_1) was defined as the input signal current through the photon-emitting diode. Therefore,

$$i_1 = \frac{v_{input}}{R_s+R_{GaAs}+2R_{si}} \quad , \qquad [55]$$

where R_s is the effective generator impedance (15 ohms) for the experiments of Chapter IV and R_{GaAs} and R_{si} are the forward dynamic resistances of the GaAs and silicon diodes. Since the forward current in both diodes was between, typically, twenty and thirty milliamperes, these dynamic resistances were taken as one ohm for these calculations. Thus,



All Resistor Values in ohms

Figure 7. Equivalent alternating current circuit for the isolator-preamplifier.

$$i_1 = \frac{v_{input}}{18} \quad . \qquad [56]$$

The gain of the overall circuit is defined as

$$A_o \overset{\Delta}{=} \frac{v_o}{v_{input}} \quad . \qquad [57]$$

Then,

$$A_o = 0.8 \times 10^5 \frac{G}{18} = \frac{0.8 \times 10^5 (3 \times 10^{-4})}{18} = 1.33 \quad . \qquad [58]$$

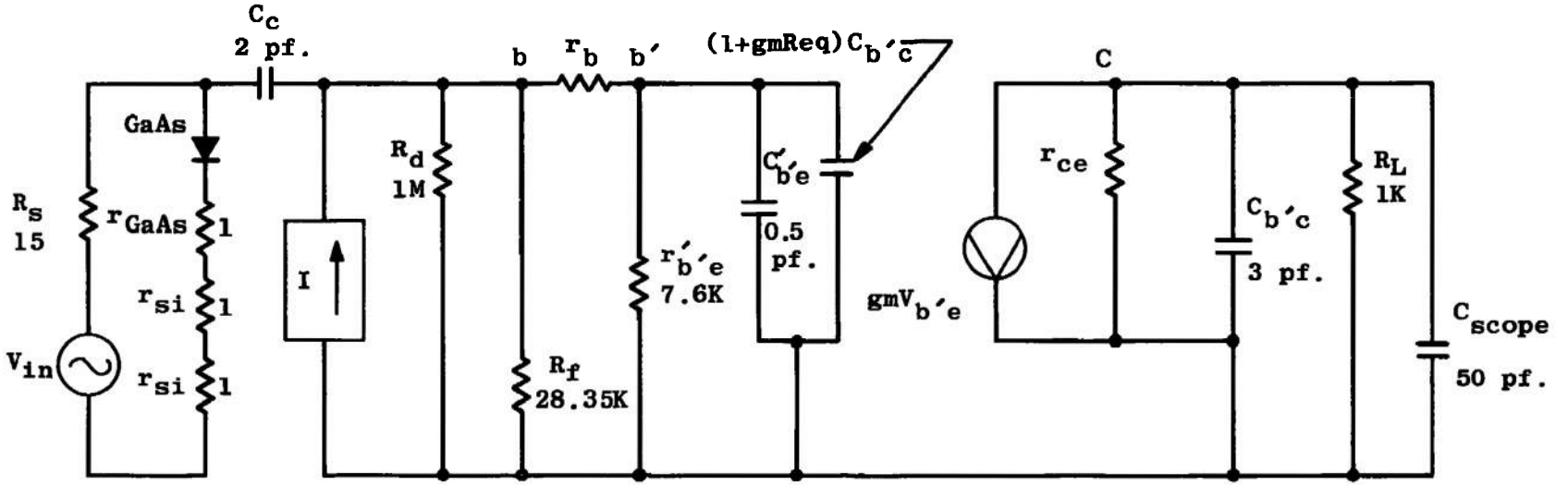
The measured gain was found to be 1.6. This agreement is considered to be acceptable.

III. CALCULATED CIRCUIT FREQUENCY RESPONSE

The input circuit, Figure 1, page 4, shows the signal source connected directly across the forward biased GaAs diode. The frequency response of the input network is limited by the transfer function of the photon emission. From the specification sheet (6), the high frequency break point (-3 decibels) is ten megahertz.

Figure 8 is the high frequency equivalent circuit for the preamplifier unit. The input high frequency break point is

$$f_i = \frac{1}{2\pi RC} \quad , \qquad [59]$$



All Resistor Values in ohms

Figure 8. High-frequency equivalent circuit.

where

C is the equivalent input capacitance and

R is the total resistance shunted across C .

The total capacitance of the input circuit is

$$C \approx C'_{b'e} + (1 + gmReq)C_{b'c} , \qquad [60]$$

where

$$C_{b'c} = 3 \text{ picofarads} ,$$

$$gmReq \approx \frac{\beta R_L}{R_i} = \frac{(10^2)(10^3)}{7.6x10^3} = 13 \qquad [61]$$

and

$$C'_{b'e} = \frac{1}{\omega_\beta r'_{b'e}} . \qquad [62]$$

Since

$$\omega_\beta = 2\pi f_T ,$$

$$f_T = \text{bandwidth}$$

$$= 500 \times 10^6 \text{ hertz} ,$$

and

$$r'_{b'e} \approx hie + (\beta + 1)R_E = 2 \times 10^3$$

$$+ 5600 = 7600 \text{ ohms} , \qquad [63]$$

then

$$C'_{b'e} = \frac{1}{2\pi(500\text{x}10^{6})(7.6\text{x}10^{3})}$$

$$= 0.5 \text{ x } 10^{-12} \text{ farads .} \qquad [64]$$

Equation 60 then becomes

$$C \approx 0.5 \text{ x } 10^{-12} + (14)(3 \text{ x } 10^{-12})$$

$$= 42.5 \text{ x } 10^{-12} \text{ farads .} \qquad [65]$$

The total resistance in shunt with C is found from the series-parallel combination of R_f, $R'_{b'e}$, and R_d to be approximately 5,000 ohms. Substituting these values into Equation 59 yields

$$f_i = \frac{1}{2\pi RC} = \frac{0.159}{(5\text{x}10^{3})(42.5\text{x}10^{-12})}$$

$$= 750 \text{ kilocycles .} \qquad [66]$$

The output break frequency is

$$f_o = \frac{1}{2\pi R_o C_o} , \qquad [67]$$

where

$$C_o \approx C_{b'c} + C_{scope} = 3 \text{ x } 10^{-12} + 50 \text{ x } 10^{-12} \qquad [68]$$

or

$$C_o \approx 53 \text{ x } 10^{-12} \text{ farads .} \qquad [69]$$

The output resistance (R_o) is approximately equal to the load resistance (R_L) or 1,000 ohms. Substituting these values into Equation 67 yields

$$f_o = \frac{1}{2\pi R_o C_o} \approx \frac{1}{2\pi(10^3)(53\times10^{-12})} = 3 \text{ megahertz} . \quad [70]$$

The calculated frequency response curve for the isolator-preamplifier unit is shown in Figure 9.

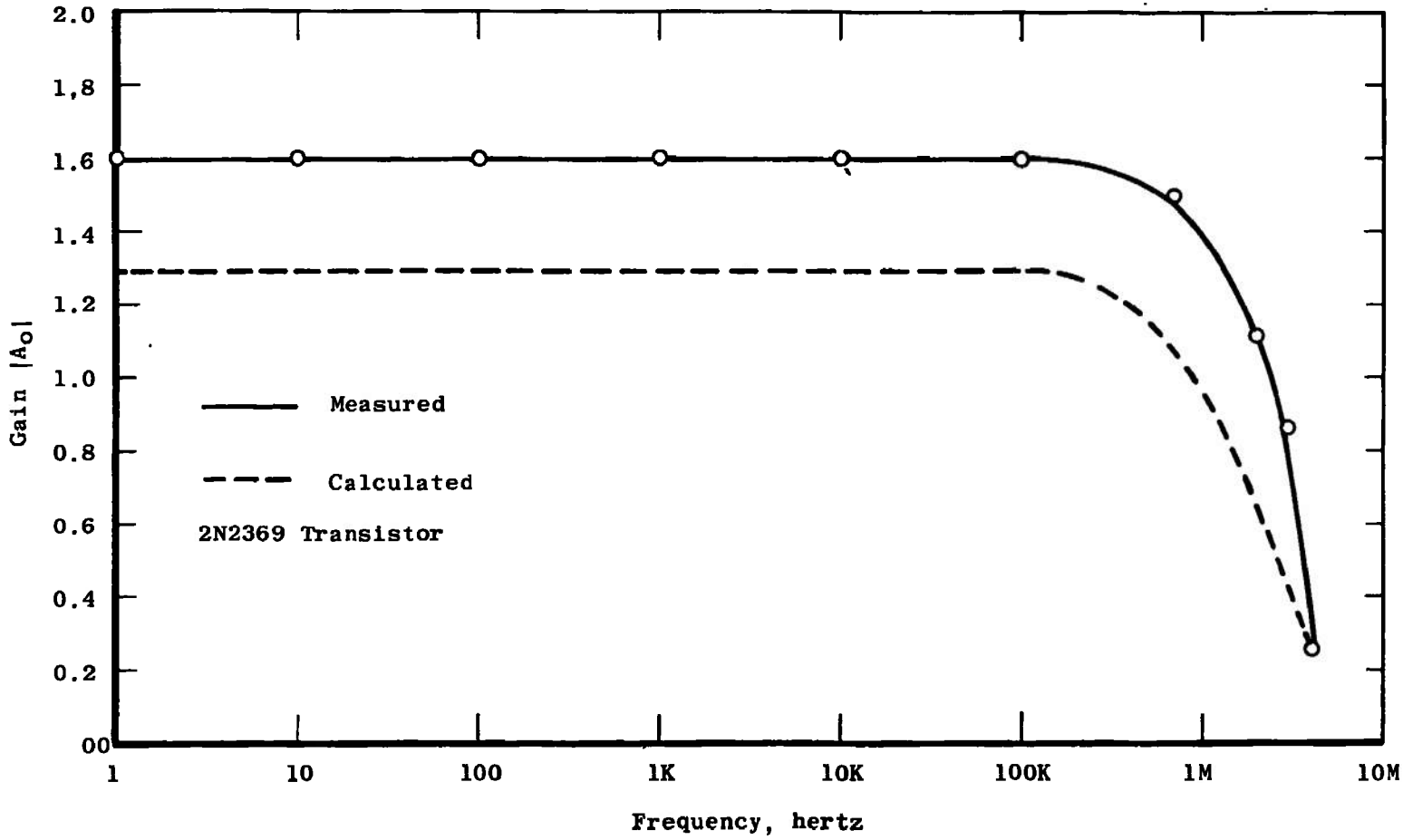


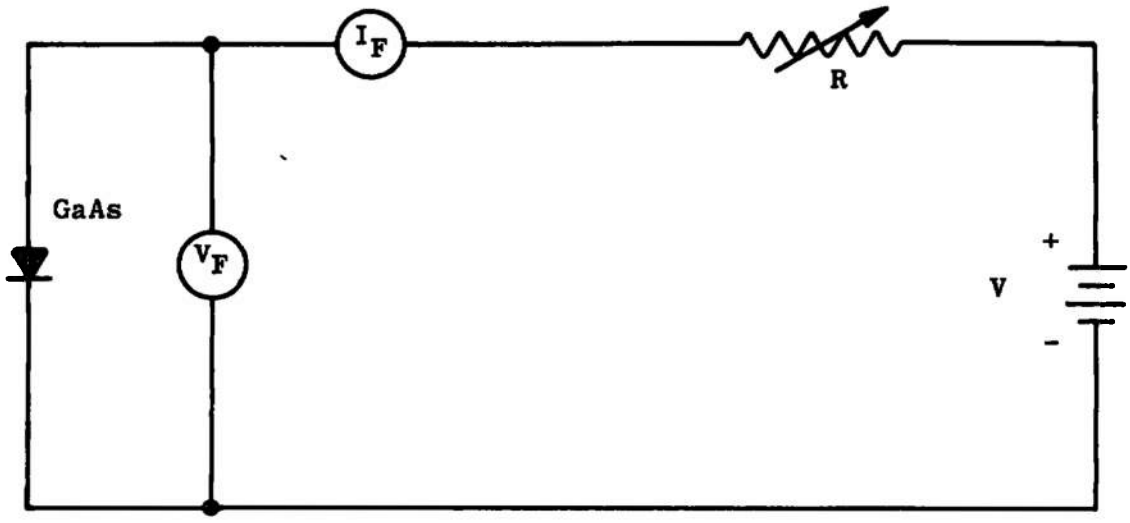
Figure 9. Frequency response of the isolator-preamplifier.

CHAPTER IV
EXPERIMENTAL ANALYSIS OF THE PHOTON-COUPLED ISOLATOR-PREAMPLIFIER CIRCUIT

I. TEMPERATURE COMPENSATION OF THE GALLIUM ARSENIDE DIODE

The effects of changing temperature on the operating characteristics of the gallium arsenide diode were investigated in order to devise a temperature compensating network. The first experiment was to determine the change in forward current with a change in forward voltage while holding the temperature constant at 21°C. Figure 10 shows the experimental circuit. The forward voltage (V_F) was varied in small increments from 0.4 to 1.24 volts, and the current at each point was recorded. The data from this experiment are shown in Figure 11. As was anticipated from the theory, forward current (I_F) increased very little for small values of V_F (from zero to approximately 0.9 volts). For values of V_F above 0.9 volts, I_F increased very rapidly. For a constant temperature of 21°C, this curve was repeatable.

The second experiment conducted was to determine the change in V_F brought about by a change in temperature while maintaining a constant value of I_F. The experimental circuit



GaAs - Gallium Arsenide Diode
I_F - Weston Milliampere Meter Model 622
V_F - Vacuum Tube Voltmeter HP410B
R - Precision Helipot 5000 ohms
V - Regulated Power Supply

Figure 10. Experimental circuit for determining the V_F-I_F curve for a GaAs diode.

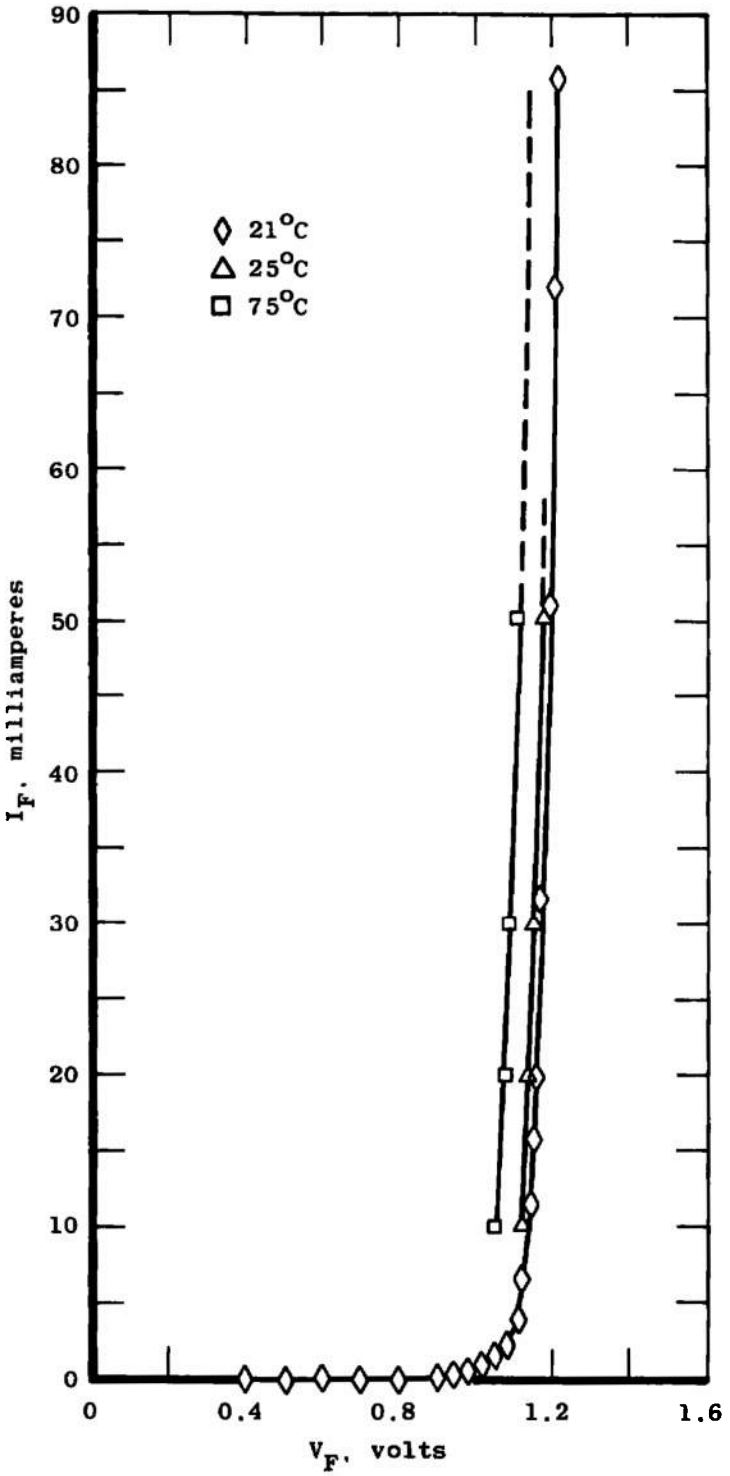


Figure 11. GaAs forward current versus forward voltage for varying temperature.

for this test was the same as for the first experiment except the GaAs diode was placed inside a Central Scientific Company temperature controlled oven. Constant values of I_F ranged from ten to fifty milliamperes while the temperature was allowed to vary from 21 to 75°C. The data from this experiment are shown in Figure 12. It is interesting to note that in the study of the characteristics of the diode it was predicted that the forward voltage across a diode would decrease almost linearly with an increase in temperature for a constant forward current.

Other interesting observations, as predicted by the theory, were also made at this point. As seen in Figure 12, at 21°C, the values for V_F at the various values of I_F correspond to the values of V_F and I_F in Figure 11. Other values of temperature were selected from Figure 12, and their corresponding values of V_F and I_F determined. These values were then plotted in Figure 11, and the V_F-I_F curves for varying temperature were plotted. Figure 11 shows the effect of increasing temperature from 21 to 25 to 75°C. Another way of looking at the curves of Figure 11 is to visualize the voltage V_F remaining constant with a change in temperature and observe the change in current. As predicted by the theory, this increase appears to be exponential.

If a stable system is to be maintained, the forward current (I_F) must be constant for a change in temperature.

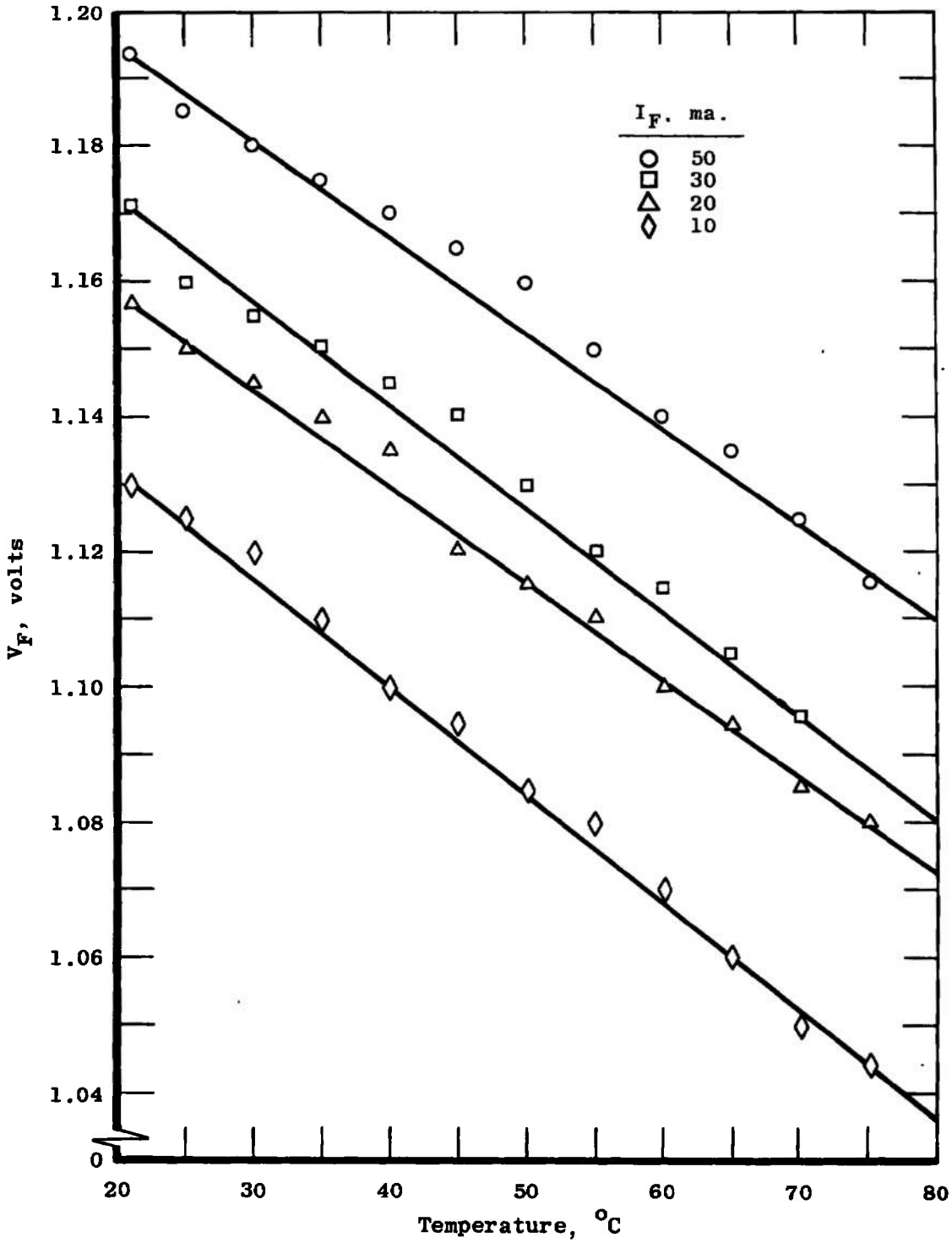


Figure 12. GaAs forward voltage versus temperature change for constant forward current.

It can also be seen in Figure 11, page 42, that if the voltage V_F were decreased with an increase in temperature, I_F could be maintained constant. For example, from Figure 11 it is seen that with an ambient temperature of 21°C and V_F equal to 1.18 volts, I_F is equal to thirty milliamperes. If the temperature increased to 75°C but the bias voltage decreased to 1.09 volts, the forward current would remain at thirty milliamperes.

The ambient temperature V_F-I_F curve for two 1N661 diodes in series was determined by use of an experimental circuit such as the one shown in Figure 10, page 41. Values of voltage between 0.4 and 1.64 volts were applied and the current readings were recorded. These values are shown in Figure 13. As was done with the GaAs diode, the 1N661 diode was placed in the Central Scientific oven. Constant values of I_F which ranged from 3.5 to 10 milliamperes were maintained. For each of these values of I_F, the temperature was varied from 21 to 75°C. The voltage V_F was recorded at each temperature point. These data are shown in Figure 14. Figure 14 shows that at 21°C the values for V_F at the various values of I_F correspond to the values of V_F and I_F in Figure 13. The values of V_F and I_F for 25°C were determined from Figure 14 and plotted in Figure 13.

Figure 15 shows the GaAs diode properly biased with the 1N661 diode circuit. The resistor R was adjusted to

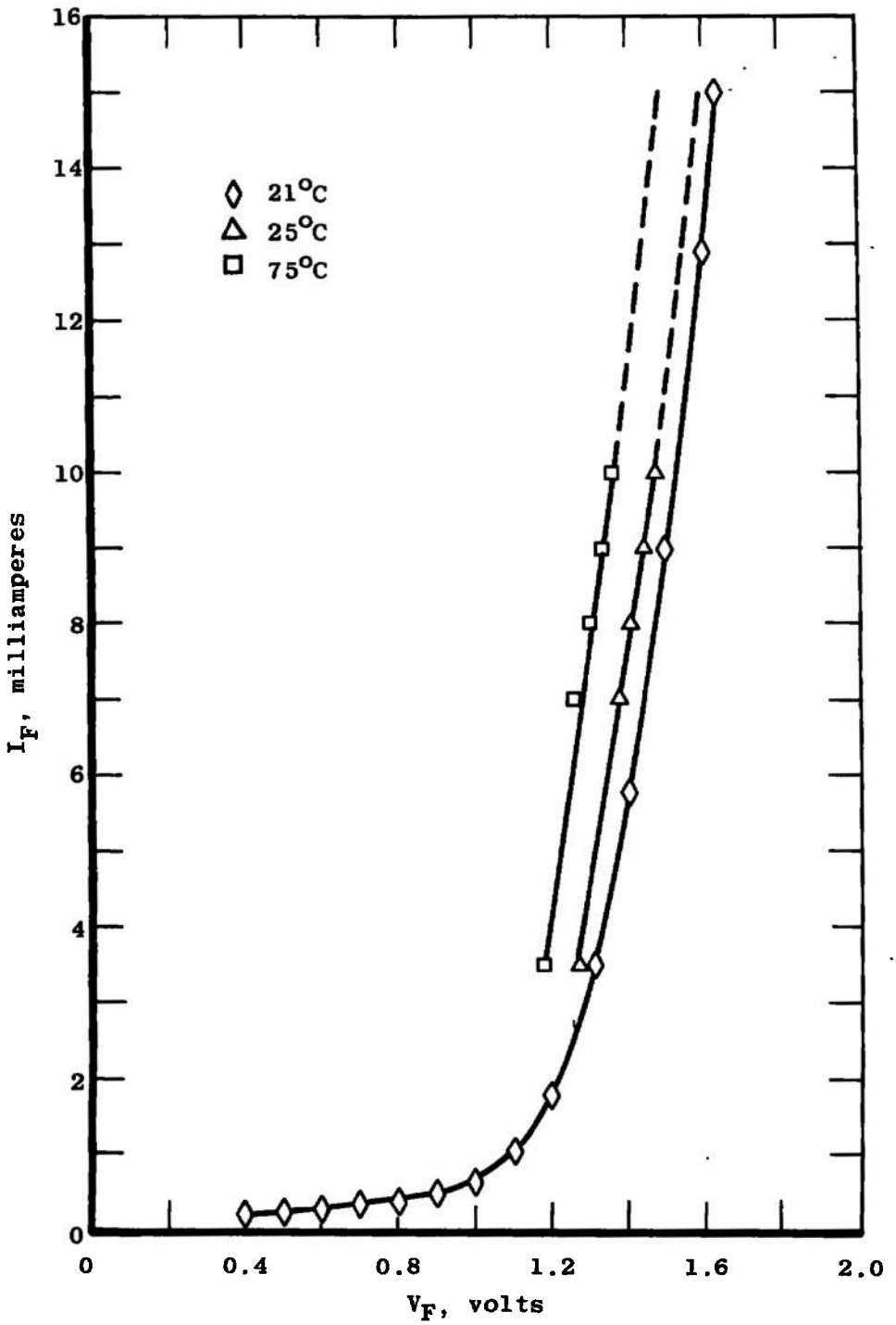


Figure 13. 1N661 forward current versus forward voltage for varying temperature.

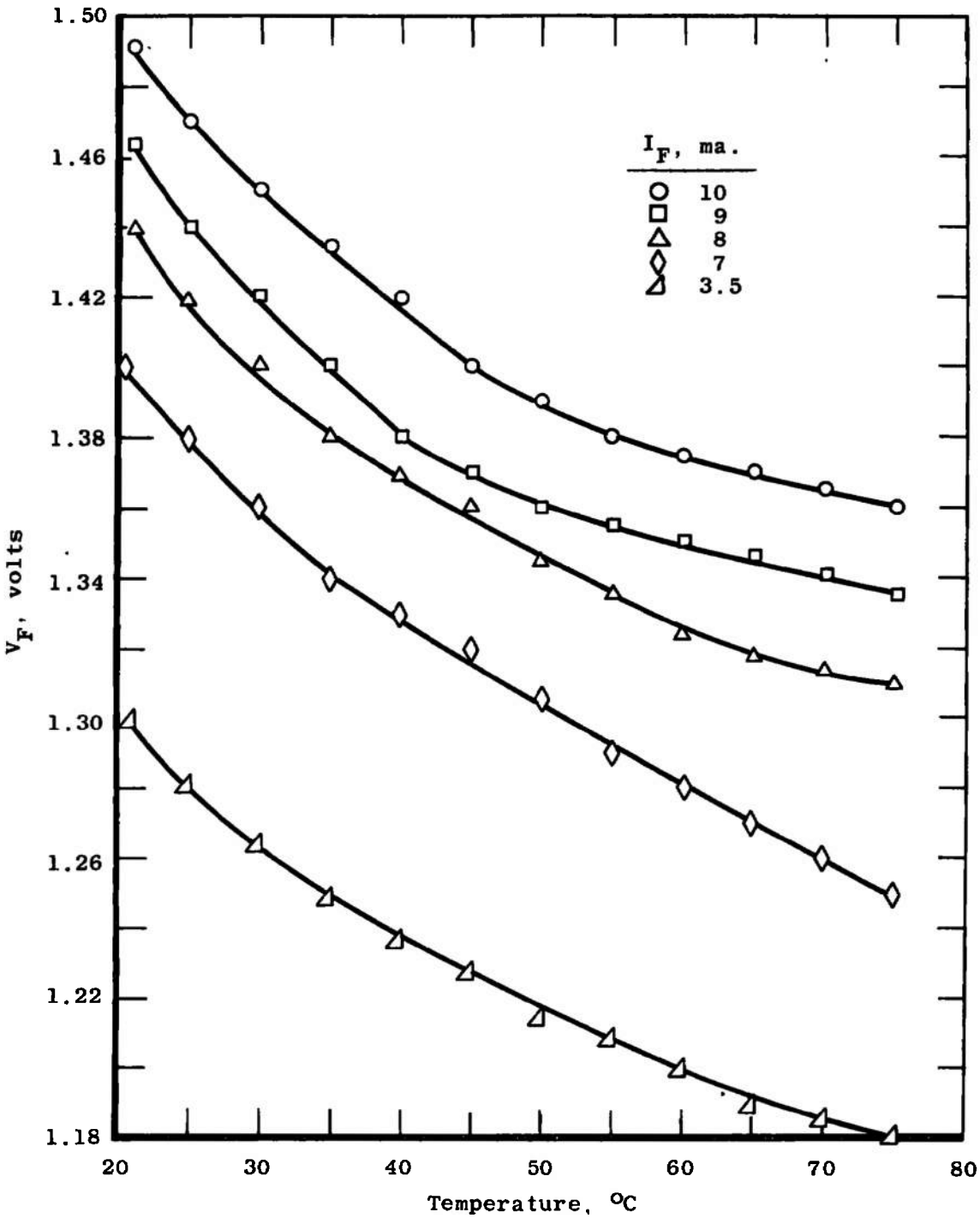
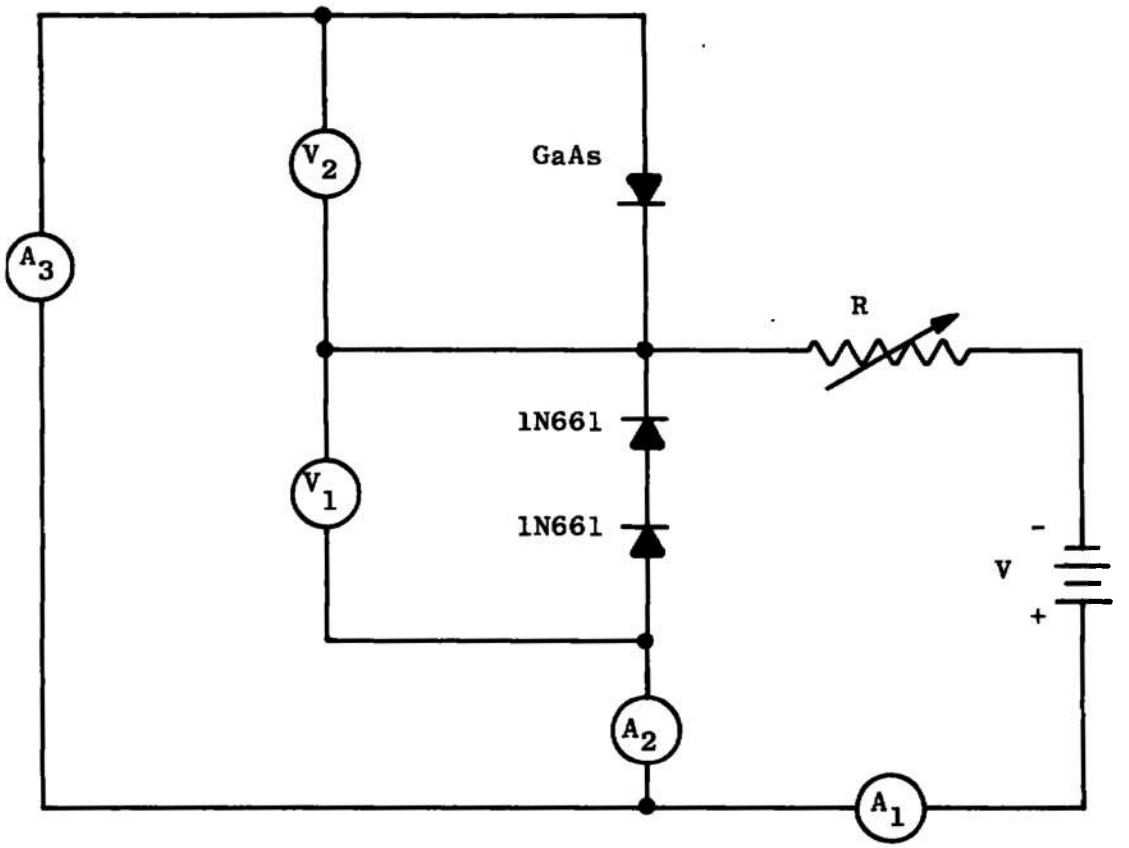


Figure 14. 1N661 forward voltage versus temperature change for constant forward current.



GaAs - Gallium Arsenide Diode
1N661 - Silicon Diode
V_1 - Vacuum Tube Voltmeter HP410B
V_2 - Vacuum Tube Voltmeter HP410B
A_1 - Weston Milliampere Meter Model 931
A_2 - Weston Milliampere Meter Model 931
A_3 - Weston Milliampere Meter Model 622
V - Six Volt Eveready "Hot-Shot" Battery
R - Precision Helipot 5000 ohms

Figure 15. Experimental circuit for determining the temperature stability of the GaAs diode circuit when biased by a 1N661 diode.

allow thirty milliamperes of current to flow through the GaAs diode. Both the GaAs and the 1N661 diodes were placed in the temperature oven, and the temperature was varied from 21 to 65°C. These data are shown in Figure 16. Although the voltage across the GaAs diode and both voltage and current in the bias circuit varied, the current through the GaAs diode remained constant at thirty milliamperes.

Thus it appears that the GaAs diode can be adequately temperature stabilized by the use of 1N661 silicon diodes in the bias network.

II. TRANSFER CHARACTERISTICS OF THE GALLIUM ARSENIDE TO PIN PHOTODIODE

The transfer characteristics from the GaAs diode to the PIN photodiode were next investigated. With the experimental circuit connected as shown in Figure 17, values of reverse bias ranging from zero to minus seventy volts were applied to the photodiode. With constant values of input current to the GaAs diode ranging from two to thirty milliamperes, the variations of PIN reverse current were observed. The data taken at 21°C were plotted in Figure 18. These data indicate the current source nature of the isolator output.

The circuit in Figure 19 was used to determine the temperature effects on the GaAs diode and the photodiode with

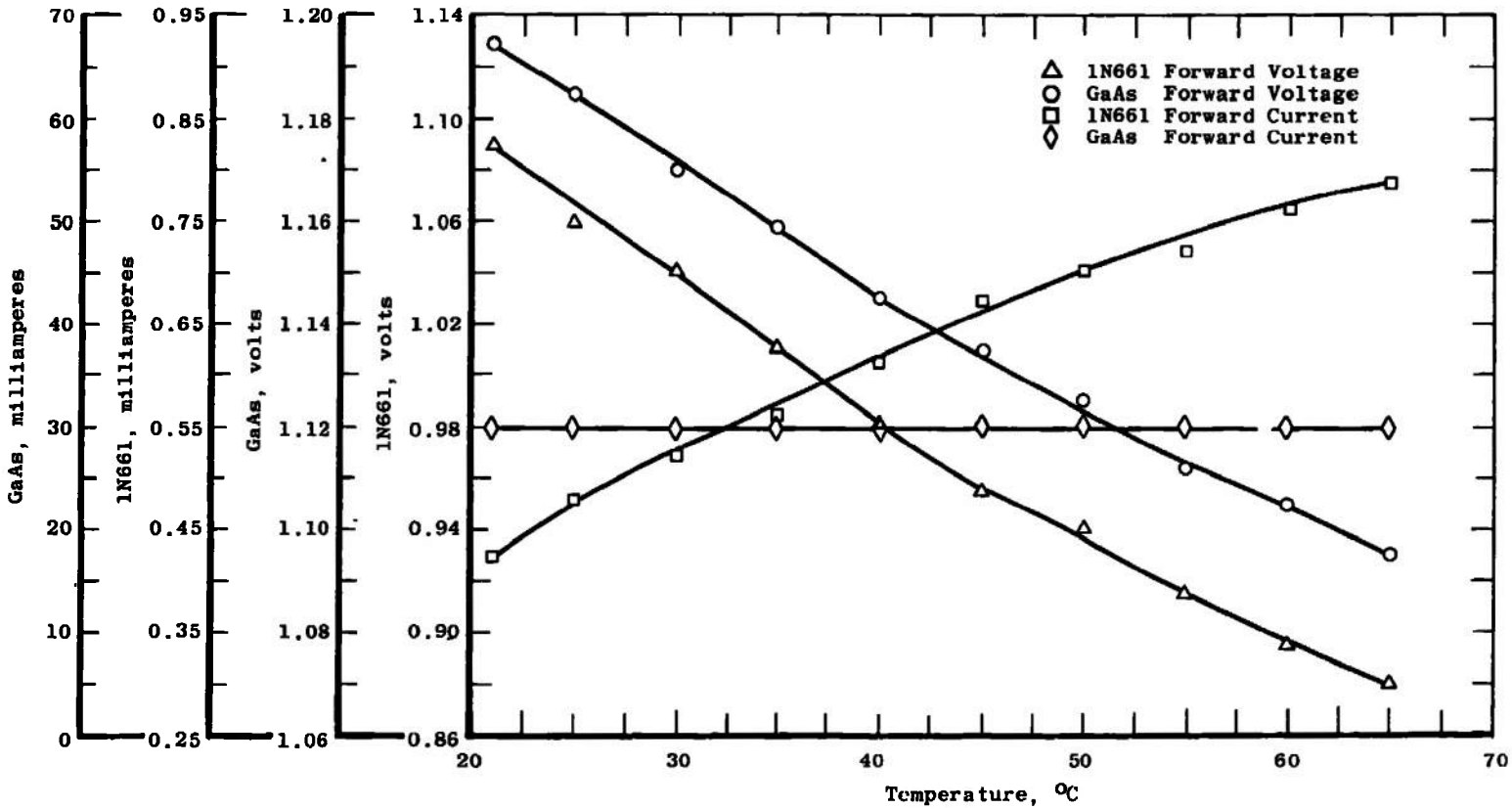
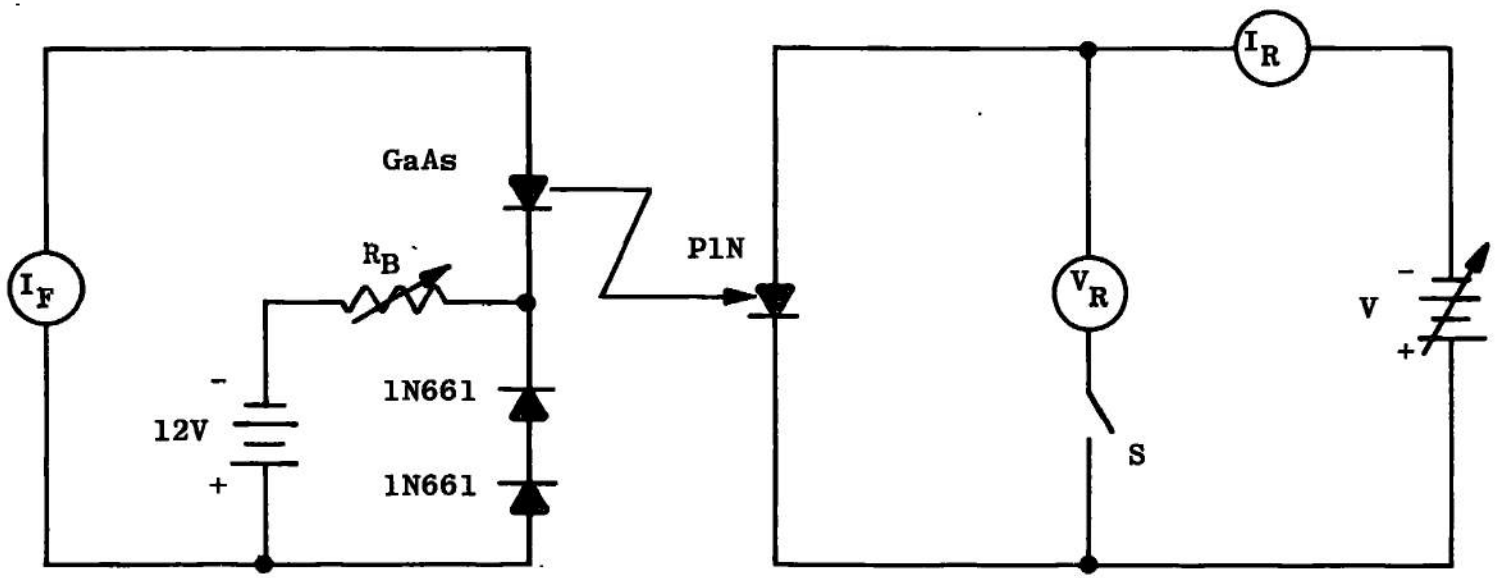


Figure 16. Current and voltage variations with temperature for a GaAs diode biased with a 1N661 diode.



GaAs-PIN - Gallium Arsenide-Pin Photo Diode
V_R - Vacuum Tube Voltmeter HP410B
I_R - Microampere Meter Simpson Model 620
V - Regulated Power Supply
I_F - Weston Milliampere Meter Model 622
S - Switch

Figure 17. Experimental circuit for determining the V_R-I_R curves for the PIN photodiode for various input current levels to the GaAs diode.

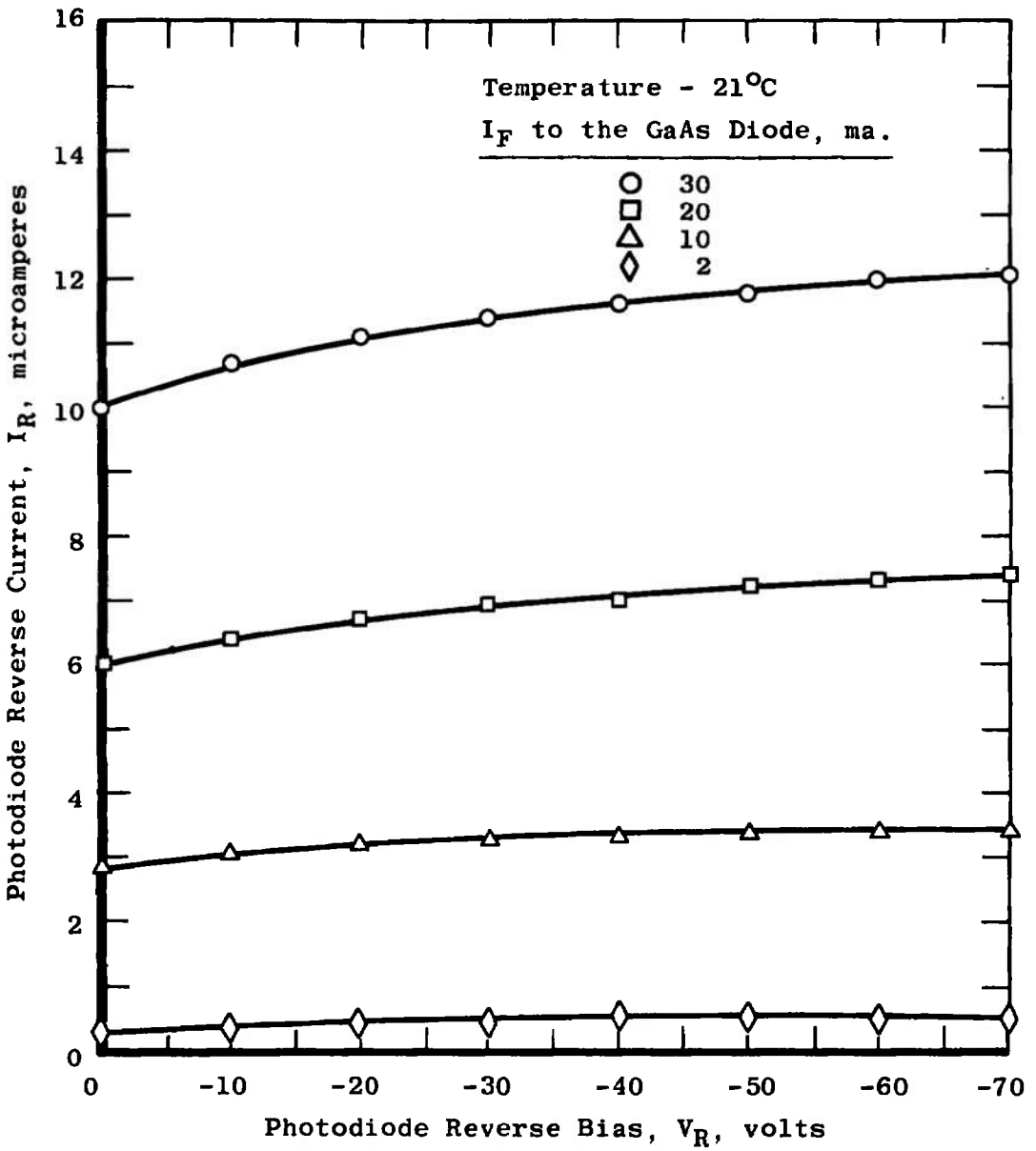
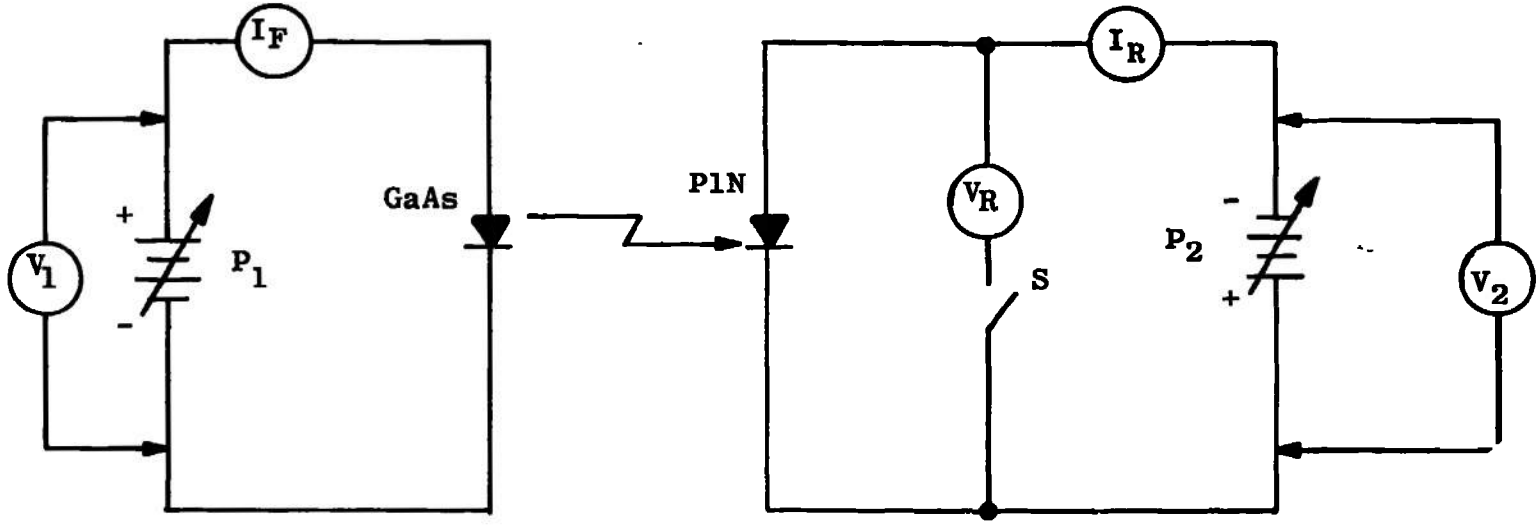


Figure 18. Photodiode reverse current versus reverse voltage for constant GaAs input current.



GaAs-PIN - Gallium Arsenide-PIN Photodiode
P_1 - Regulated Power Supply
P_2 - Regulated Power Supply
V_1 - Vacuum Tube Voltmeter HP410B
V_2 - Vacuum Tube Voltmeter HP410B
I_F - Weston Milliampere Meter Model 622
I_R - Microampere Meter Simpson Model 260
V_R - Vacuum Tube Voltmeter HP410B
S - Switch

Figure 19. Experimental circuit for determining the temperature stability of the GaAs diode and the PIN photodiode without external temperature compensation.

the GaAs diode uncompensated. The voltage (V_F) across the GaAs diode was set at 1.18 volts to deliver a current (I_F) of thirty milliamperes at 21°C. The forward voltage was maintained constant by the regulated power supply. The voltage across the photodiode was set at minus ten volts and was also maintained constant. The temperature of the isolator was varied only from 21 to 45°C since the GaAs diode current reached 100 milliamperes at this point. The values of photodiode current for incremental steps of temperature are shown in Figure 20. The current in the photodiode increased rapidly with temperature to approximately 35°C. From this point, the change in output current with temperature increased only slightly with temperature.

The circuit in Figure 15, page 48, was again set up and placed in the oven. This circuit made use of the 1N661 diode bias compensation network which holds the GaAs current constant for changing temperature. Therefore, any change in output current with temperature represented the effects of temperature on the efficiency of the photon generating, coupling, and detection processes. It is not convenient to physically separate these three processes although it is realized that each is affected by temperature. In this experiment, the photodiode bias was set at minus ten volts.

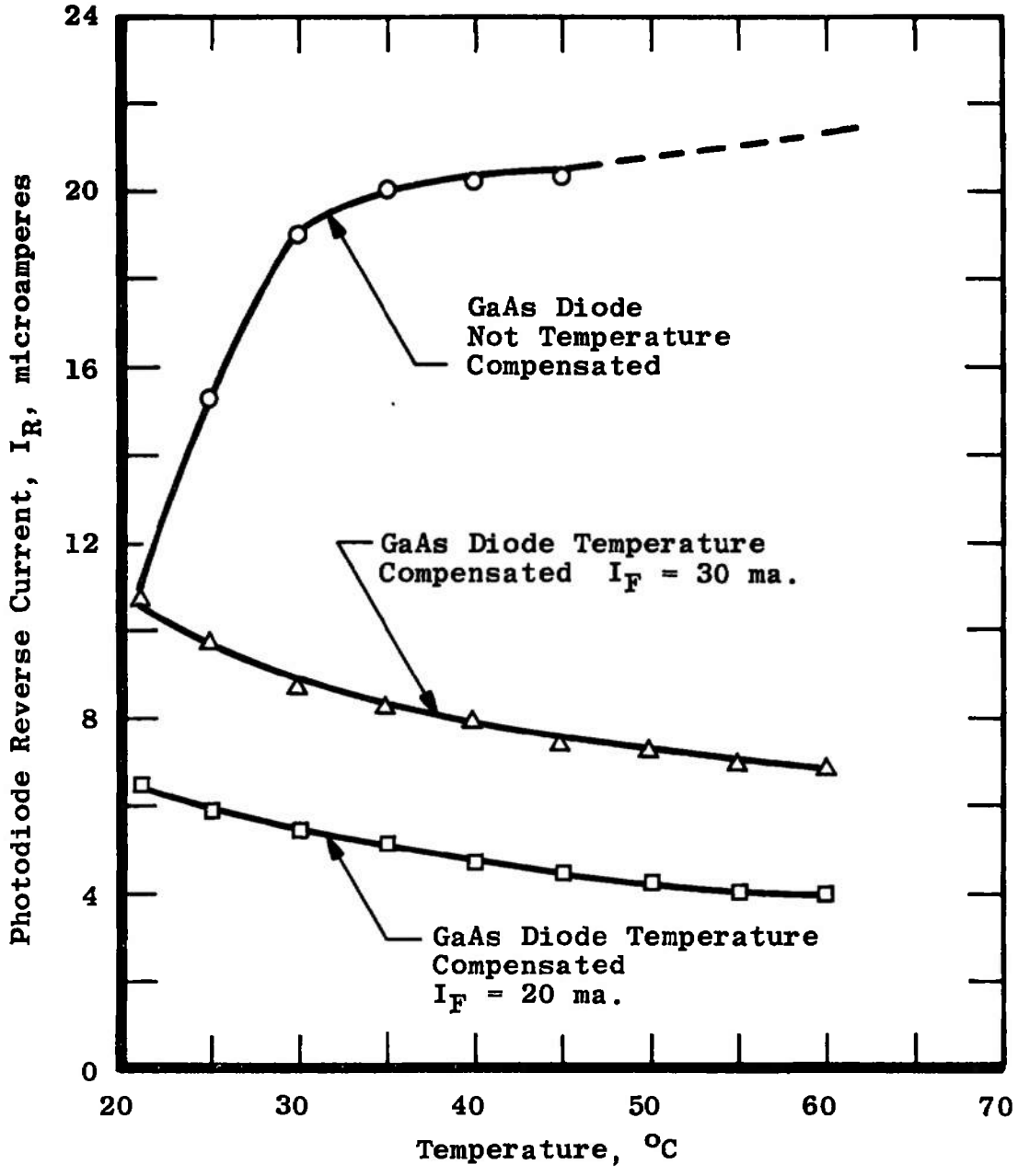


Figure 20. Photodiode reverse current versus temperature for compensated and uncompensated input.

The temperature was varied from 21 to 70°C with GaAs inputs of twenty and thirty milliamperes. These data are plotted for comparison in Figure 20.

Although the GaAs current was held constant, the photodiode current decreased slightly with increased temperature. The decaying output current represents the change in the overall efficiency of the photon-coupled isolator unit.

By choosing other diodes, the GaAs bias current could have been made to increase slightly with temperature, and a "flat" transfer characteristic could have been obtained. However, this "overcompensation" was used to advantage since the photodiode output was fed directly into the base of the preamplifier transistor which required a decreasing bias current with increasing temperature.

It should be noted that the current readings were made with a Simpson Model 260 multimeter with a microampere scale. This meter has very limited accuracy on the low level scales, but since all microampere measurements were made with the same instrument, the comparisons presented should be valid.

III. TEMPERATURE EFFECTS ON THE OVERALL CIRCUIT

The effects of temperature on the overall circuit were investigated using the circuit in Figure 1, page 4. The bias current to the GaAs diode was set at thirty

milliamperes, and the reverse bias on the photodiode was set at 8.7 volts. The potentiometer in the base circuit of the preamplifier was adjusted for zero millivolt output. The output was measured on an oscilloscope An oscillator and oscilloscope were used to apply a thirty millivolt peak-to-peak sine wave across the input resistor (R_s). At ambient temperature, the frequency was varied from zero hertz to five megahertz and the output was observed. The output was constant at fifty millivolts over the range from zero hertz to approximately 200 kilohertz. At this point, the amplitude began to drop so that at a frequency of three megahertz the output was only twenty-five millivolts. The data from this experiment are plotted in Figure 9, page 39, for comparison with the calculated data.

The circuit, except for the batteries, was then placed in the oven, and the frequency response was checked from zero hertz to 700 kilohertz at 45°C. No appreciable change was observed in the amplitude of the data; the amplitude-frequency followed that shown in Figure 9.

The d-c drift of the isolator-amplifier was next investigated. The GaAs bias current was set at thirty milliamperes with no external signal applied. The preamplifier bias potentiometer was adjusted for zero output. The circuit, except for the batteries, was placed in the oven, and the output drift with temperature was observed on an

oscilloscope. The output change was less than 0.5 millivolt for temperatures up to 35°C. However, as temperature increased above this point, the output varied almost linearly with temperature until it reached eight millivolts at 60°C. These data are shown in Figure 21. For high temperature environment, more temperature stabilization is required.

To determine the magnitude of the problem of stabilizing the battery output with temperature change, the batteries were placed in the oven with the circuit. The temperature was varied from 21 to 60°C with the results as shown in Figure 21. This plot is given to challenge the reader with the problem which still exists.

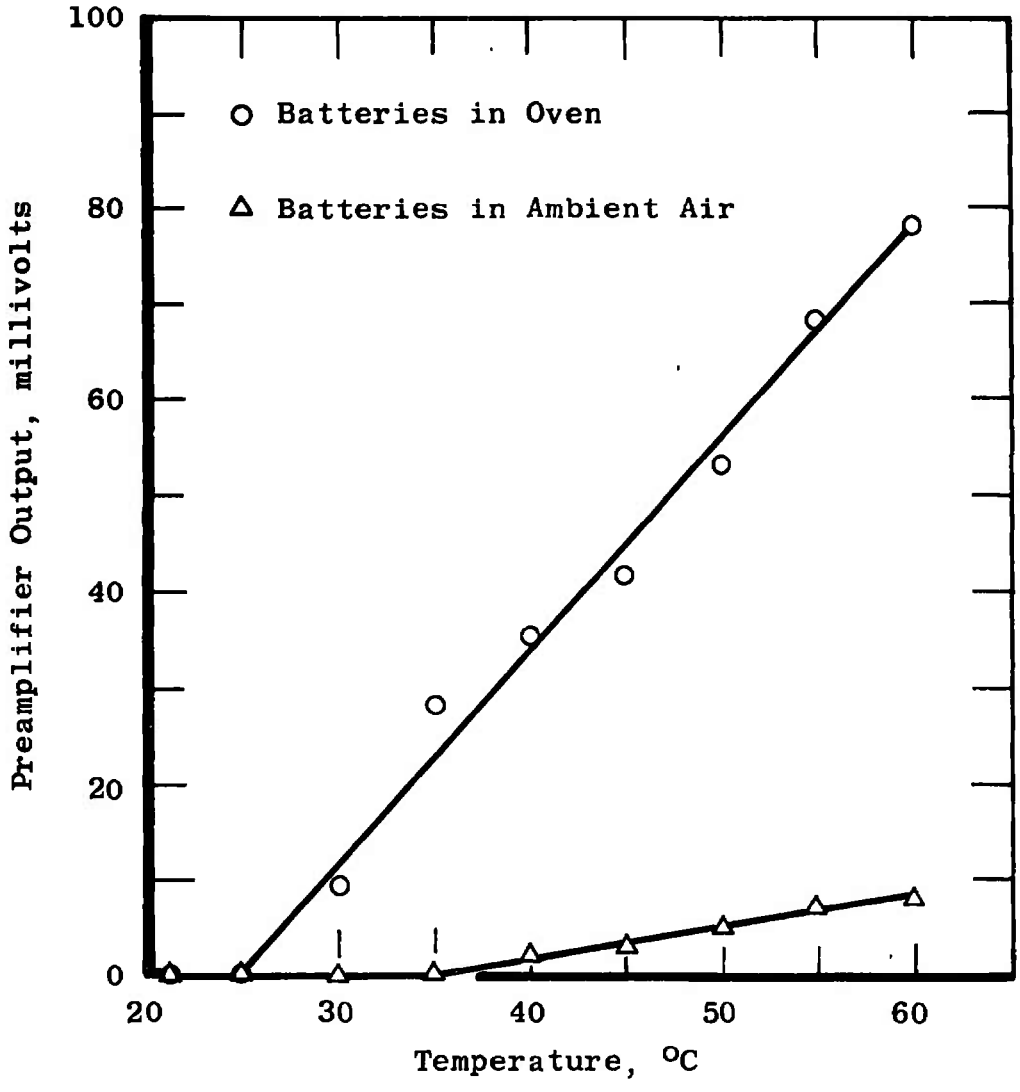


Figure 21. Temperature stability of the isolator-preamplifier unit.

CHAPTER V
CONCLUSIONS AND DISCUSSION

From the experimentation thus far completed, the conclusion can be reached that the gallium arsenide photon-coupled isolator is a useful input device for a direct-coupled isolator-amplifier. The problem of temperature instability is not insurmountable.

By using the diode biasing arrangement presented, three major obstacles are overcome. First, the dynamic impedance of the input circuit can be as low as desired by simply lowering the value of R_s. For measuring signals from a very low impedance source, R_s could be placed in series with the GaAs diode for current limiting. Second, the input is direct coupled to the signal source. Third, the temperature characteristics of the bias diode are such as to stabilize the current through the GaAs diode for changes in ambient temperature. The diode bias arrangement also aids indirectly in stabilizing the preamplifier since the transfer characteristic of the GaAs diode-to-PIN diode decreased with temperature.

The emitter resistor and the collector-to-base feedback resistor aid in stabilizing the transistor against

changes in reverse saturation current and changes in β for an increase in temperature.

Areas for future investigation should include placing a silicon diode across the PIN diode in an attempt to further decrease reverse saturation current effects and to maintain a constant base current for changing temperature. The remaining major obstacle is that of stabilizing the battery circuits.

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13 ABSTRACT

A theoretical and experimental analysis of a temperature-stabilized, photon-coupled, isolator-preamplifier circuit was conducted. Input signals were applied to a gallium arsenide diode which in turn emitted infrared radiation in proportion to the instantaneous forward current. The radiation was guided through a light pipe into a silicon PIN photodiode. The signals which resulted at the photodiode were therefore controlled by, but electrically isolated from, the input. Both the input circuit and the preamplifier were investigated for temperature effects, and circuits were designed to limit these effects.

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